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A Novel Design of U-Slotted SIW Based Wideband Antenna

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***Abstract*—In this paper, we proposed a novel design of U-slotted SIW antenna. Our antenna design is aimed to cover upper K-band and lower Ka-band spectrums, specifically from 24 GHz to 32 GHz. It has a compact square size of 5.2 x 5.2 mm^2. We use a rectangular truncated corner to optimize the square radiator. The optimized rectangular truncated corner size of 2 x 0.8 mm^2 gives an impedance bandwidth of 7.87 GHz. SIW cavity is constructed by using multiple metallic via-holes which are drilled in a dielectric substrate establishing. Next optimization, applying the U-shaped slot and SIW structure yield a wider impedance bandwidth of 8.89 GHz, there is about 1.02 GHz of impedance bandwidth enhancement. In addition, the SIW structure gives a higher gain of 7.63 dB and decreases the sidelobe level of -12.1 dB. Implementation of the SIW structure significantly decreases the size of antenna while keeping the antenna parameter's performances.**

***Keywords*—U-shaped slot, SIW, via-holes, truncated corner**

I. INTRODUCTION

IN recent years, wireless communication systems grow rapidly. It has driven technological development in wireless devices. There are several important devices in a wireless communication system such as filter, mixer, duplexer, waveguide, antenna, and etc. An antenna is one of the essential parts of wireless devices, it is a transducer. The antenna converts electric currents moving in conductors into radio frequency propagating through space or vice versa. A wireless transmitter system supplies an electric current to the antenna, it radiates the energy from the electric current as electromagnetic waves. As a receiver, the antenna captures some of the power of an electromagnetic wave in order to produce an electric current. Some wireless communication applications require the antenna as a front-end equipment including mobile wireless communication, satellite communication, wireless sensor networks, wireless fidelity, and etc. Nowadays, a microstrip antenna has been recognized as one of an applicable antenna in wireless communication systems due to its capability to have lightweight, low cost and low profile characteristics but it has a constraint in terms of size. Therefore, the size of microstrip antenna is becoming a serious issue. The microstrip antenna must have a compact size to meet the requirement of the size limitation of the wireless transmitter. The researchers are challenged to develop a technique that getting a compact size of the antenna with its high performance. Several antenna's parameters are always improved including gain, bandwidth, mutual coupling, polarization, and etc. Reducing mutual coupling, the author in [1] used slotted meander line resonators to minimize mutual coupling between antenna elements. The combination of split-ring resonators (SRR) and electromagnetic bandgap (EBG) as a decoupling element [2]. In [3], it proposed a symmetric feeding network to reduce mutual coupling. [4]. Coplanar strip wall between two or more antenna elements was reported in [5]. Another approach for mutual coupling reduction using a frequency selective surface (FSS). The gain enhancement is achieved using the zero-index property of the single-layer metamaterial (MTM) superstrate, there is a 6.42 dB of gain improvement [6]. In [7], a stacked H-shaped patch antenna with an open ring is proposed to improve the antenna gain. A configuration of printed monopole patch antenna placed symmetrically between two passband Frequency Selective Surfaces (FSSs) for bidirectional gain enhancement in X-band is presented in [8]. A novel L-slot mushroom EBG (LS-EBG) is proposed to enhance antenna gain [9].

Enhancing the impedance bandwidth, various techniques have been investigated. In [10] [11], bandwidth enhancement and additional resonance were generated by implementing multiple slots. Different structures were proposed in [12] such as a slotted cavity, metallic via-hole, triangular complementary split-ring slot, and multilayer dielectric. Multilayer dielectric reached about 40% of bandwidth improvement but its design more complex and bulky. Recently, the substrate integrated waveguide (SIW) structure has attracted the researcher's attention due to its comprehensive applications in wireless transmitters. SIW structure is a type of metallic waveguide that can be applied in a dielectric substrate by using metallic via-holes connecting the top layer (patch) and the bottom layer (ground plane). This structure can be integrated with a planar antenna. SIW structure has potentially improved the impedance bandwidth.

Based on some previous works, we propose a novel design of U slotted – closed SIW to obtain a wider bandwidth covering upper K-band and lower Ka-band spectrums. We use a closed structure of the SIW cavity which are four sidewalls applied to broaden bandwidth and enhance gain. In addition, a U-shaped slot is implemented to generate several resonances. The dimension parameters of SIW structure with via holes diameter d and via pitch p, width a_SIW, and whole-dielectric waveguide ports of width W_equivalent. In order to obtain the best value for a_SIW, with d, p and W_equivalent are given. The input reflection coefficient (S) of the transition is minimized by

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varying a_SIW. The nonlinear least-squares technique is used to obtain the final formula for the design of a SIW as follows [13]:

$$a_{SIW} = W_{equivalent} + p\left(0.766e^{(0.4482d/p)} - 1.176e^{(-1.214d/p)}\right) \quad (1)$$

with the cutoff frequency f_c , d/p ratio $(0.5 < d/p < 0.8)$, substrate permittivity ε_r and obtained a_{SIW} from (1) then the effective SIW cavity waveguide width $W_{equivalent}$ is formulated as follows

$$W_{equivalent} = \frac{C}{2f_c\sqrt{\varepsilon_r}} \quad (2)$$

II. SIW Antenna Design

The detailed geometry of the proposed U-slotted SIW antenna is shown in fig.3. It is designed on FR4 with relative permittivity (ε_r) 4.4 and height (h) 0.53 mm. there is a rectangular truncated corner applied. This U-slotted SIW antenna occupies a compact size of 5.2 mm x 5.2 mm. After we determine the size of square patch, we optimize this size by applying a rectangular truncated corner. These two rectangular truncated corners are placed in two opposite corners as pictured in fig.1. The optimized patch antenna surrounded by an outer-square ring. Our proposed antenna is aiming to cover upper K-band and lower Ka-band spectrums. It is an ultrawideband (UWB) antenna. Various sizes of rectangular truncated corner are implemented including : 2 x 0.8 mm^2, 2 x 0.7 mm^2, and 2 x 0.6 mm^2. One U-shaped slot is made in the patch layer which is fed by a probe, it will give freedom to adjust the desired broadband antenna operation spectrum. Some metallic via holes are drilled into the dielectric substrate in a periodic arrangement. These are arranged in four sides of the dielectric substrate. This metallic via holes arrangement matches with the closed SIW cavity. The existence of metallic via holes will suppress the surface waves and restricting the energy under the patch antenna.

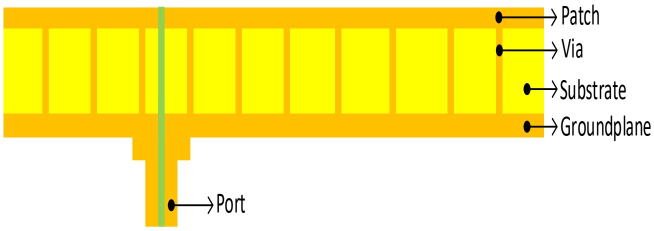

Fig. 2. Side view of U-slotted SIW antenna

In the last optimization, we apply a U-shaped slot, merge the optimized patch with the outer-square ring through a bridge with a length of L3. The metallic via-holes with its diameter W8 are drilled in all four sides of the dielectric substrate. There are thirty-six metallic via-holes with via pitch W7. Figure 2 illustrates a side view of the SIW antenna. The completely optimized design of the proposed U-slotted SIW antenna is shown in Fig.3 with detail dimensions in Table I.

TABLE I
DESIGN SPECIFICATIONS FOR U-SLOTTED SIW ANTENNA

Parameter	Value (mm)
W	5.2
L	5.2
W1	4
L1	4
W2	0.6
L2	0.6
W3	0.4
L3	0.4
W4	0.7
L4	0.8
W5	2
L5	2.8
W6	0.9
L6	0.7
W7	0.38
L7	0.15
W8	0.1

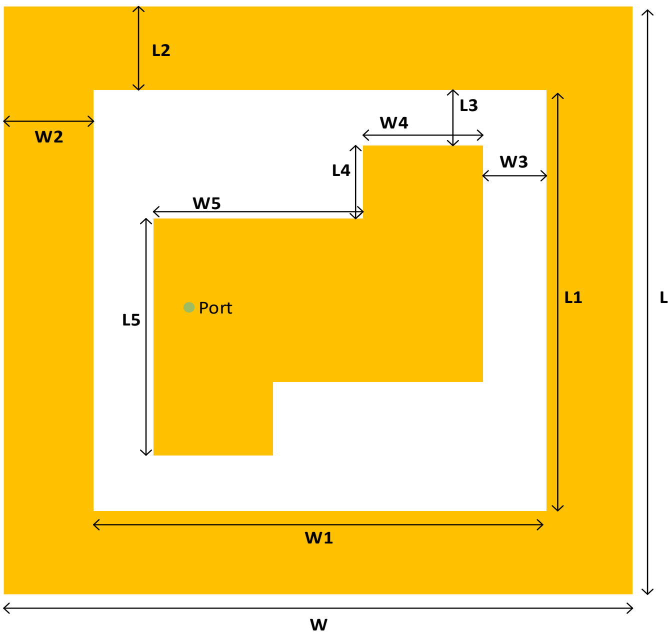

Fig. 1. Rectangular truncated corner and outer-square ring

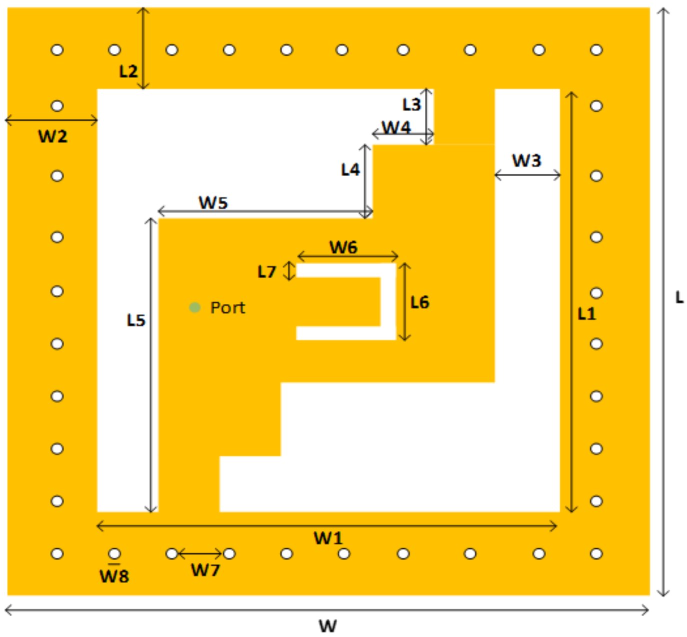

Fig. 3. Complete geometry of U-slotted SIW antenna

III. Results and Discussion

Several antenna parameters specified in the characterization include voltage standing wave ratio (VSWR), gain, impedance bandwidth, reflection coefficient and radiation pattern. Figure 4 informs us that the size of rectangular truncated corner has an impact on the S parameter and impedance bandwidth performance. There are three variations of the rectangular truncated corner sizes such as 2 x 0.8 mm^2, 2 x 0.7 mm^2, and 2 x 0.6 mm^2.

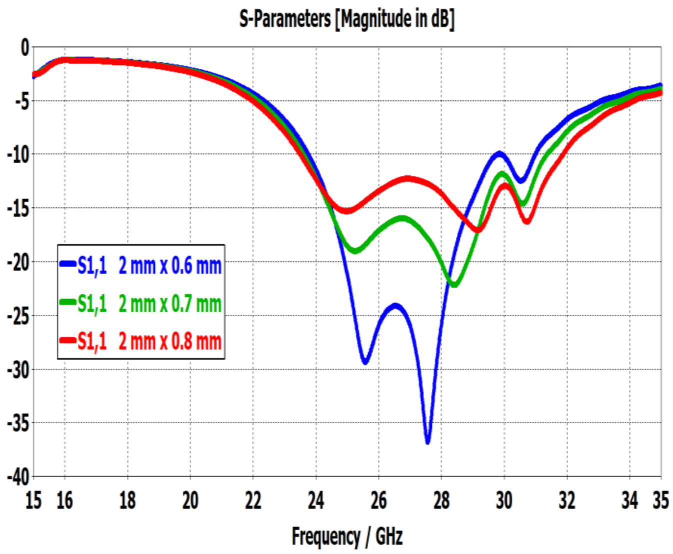

Fig. 4. S parameter (S11) as a function of various rectangular truncated corner sizes

Based on fig. 4, a wider rectangular truncated corner generates better impedance bandwidth. The size of 2 x 0.8 mm^2 creates impedance bandwidth (S11 < -10 dB) along 23.93 GHz to 31.8 GHz, there is an impedance bandwidth of 7.87 GHz while the size 2 x 0.7 mm^2 generates an impedance bandwidth of 7.51 GHz, and the last, 2 x 0.6 mm^2, yields an impedance bandwidth of 7.39 GHz. Changing the width of rectangular truncated corner shifts the resonant frequency and the level of S parameter (S11).

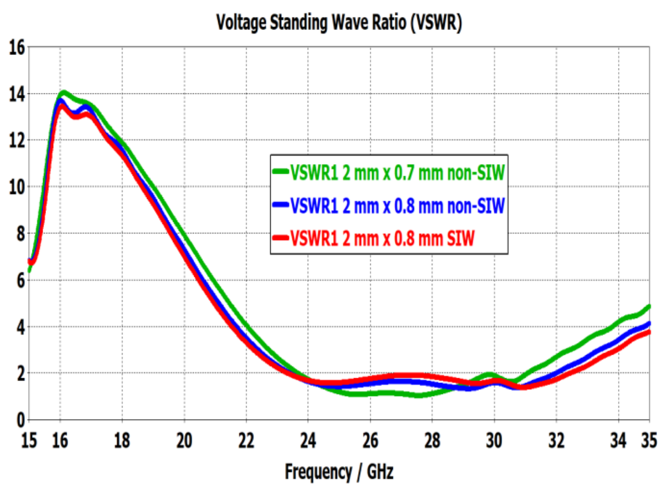

Fig.5. Performance of S parameter (S11) with and without SIW structure

As shown in fig.5, It investigates the feasibility of U-shaped slot and SIW incorporation in achieving the wideband impedance bandwidth and reflection coefficient (S11) level. Fig 5 plots the simulated reflection coefficient and impedance bandwidth the U-slotted antenna with and without SIW structure, respectively. The U-slotted SIW antenna creates a wider impedance bandwidth (<-10 dB) achieving 8.89 GHz covers from the frequency of 23.434 GHz to 32.321 GHz. There is an enhancement of impedance bandwidth of 550 MHz compared to the U-shaped slot antenna without the SIW structure.

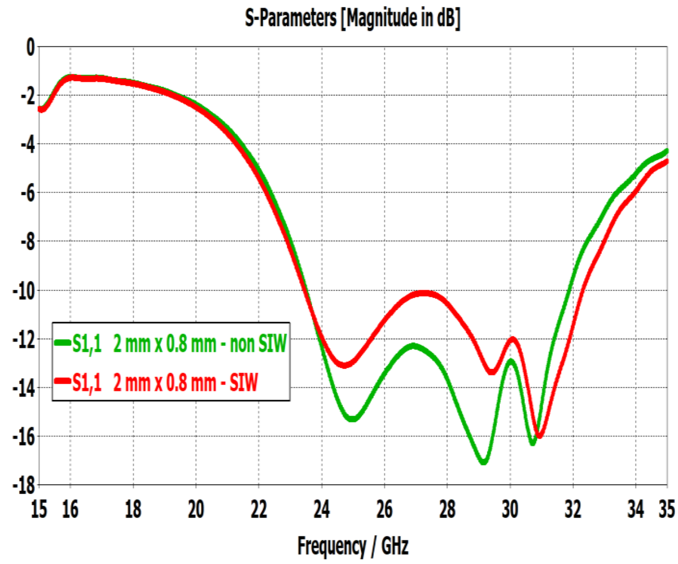

Fig. 6. VSWR profile

Figure 6 plots the level of VSWR, the U-slotted SIW antenna yields VSWR less than 2 along from 23.434 GHz to 32.321 GHz, their VSWR value in a range of 1.3 to 1.92. It means that the reflected voltage is in a range of 13 % to 31,5% of transmitted voltage.

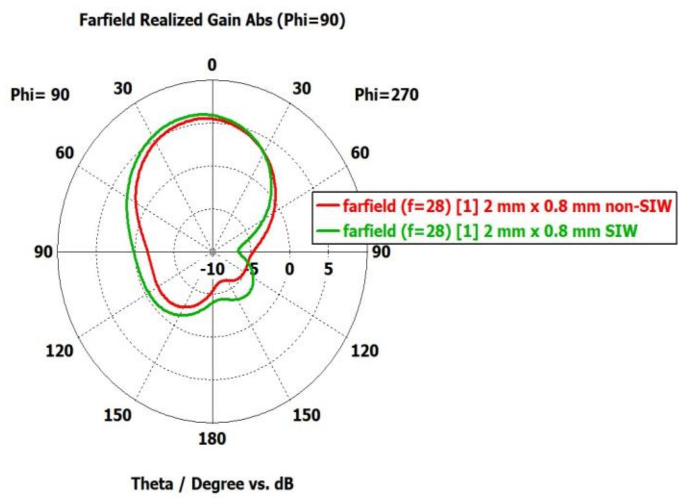

Fig. 7. A 2D of radiation pattern of the antenna at 28 GHz

TABLE II
SPECIFICATION OF A RADIATION PATTERN

	with SIW antenna (truncated corner: 2x0.8 mm^2)	without SIW antenna (truncated corner : 2x0.8 mm^2)
Main lobe magnitude/gain	6.24	5.56
Angular width (3 dB)	87°	86.4
Side lobe level	-12.1 dB	-9.4 dB

Based on fig 7 and table 2, this picture depicts the comparison of a 2D radiation pattern of U-slotted with and without SIW structure. The U-slotted antenna with SIW structure outperforms the antenna without SIW structure. The antenna with SIW structure yields a 6.24 dB of gain while without SIW just generates a 5.56 dB. Furthermore, the SIW structure also creates a lower level of sidelobe level. There are -12.1 dB for SIW structure and a -9.4 dB for without SIW structure, respectively.

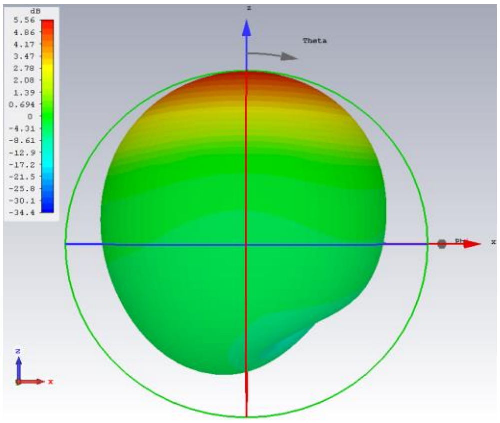

Fig. 8. A 3D of radiation pattern of U-slotted without SIW structure at 28 GHz.

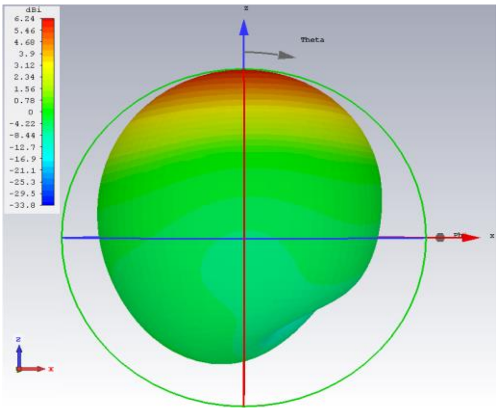

Fig. 9. A 3D of radiation pattern of U-slotted with SIW structure at 28 GHz.

In addition, fig 8 and fig 9 tell us the complete geometrical of a 3D radiation pattern of both U-slotted without and with SIW structure. These images have the same three dimensional/3D shape at a glance, but they have different numeric specifications. The red color represents the highest gain that can be produced at the main lobe.

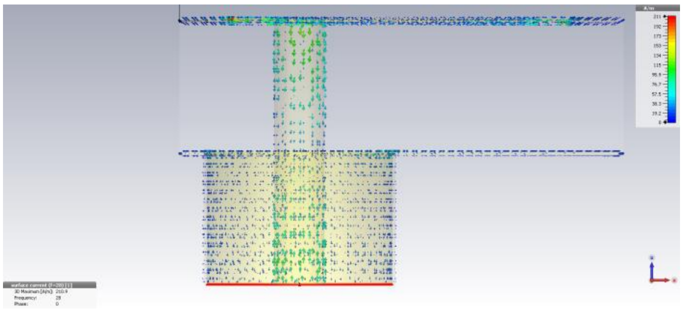

Fig. 10. Side view of surface current distribution without SIW structure

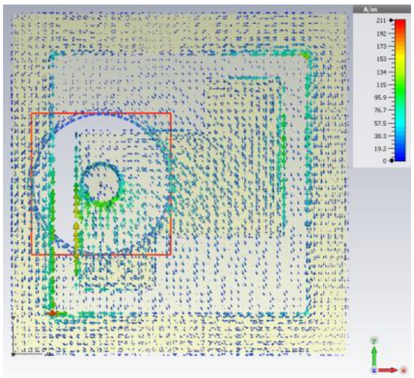

Fig. 11. Front side of surface current distribution without SIW structure

These two pictures above, fig 10 and fig 11, explain the surface current distribution without SIW structure. Fig 10 clearly tells the structure without SIW. The groundplane and radiator patch aren't connected. There aren't via holes inserted. The numerical result shows that the highest surface current without SIW structure is 211 A/m at 28 GHz.

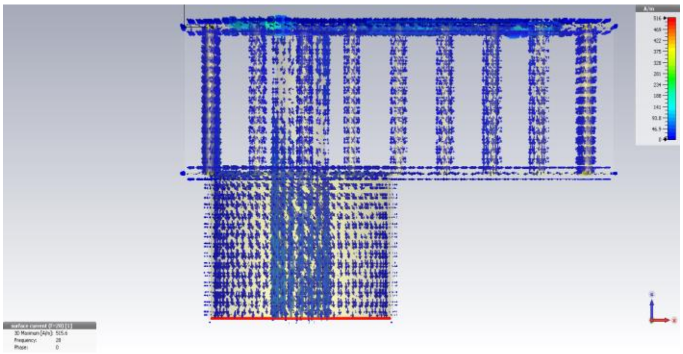

Fig. 12. Side view of surface current distribution with SIW structure

Surface current distribution with SIW structure can be seen in fig 12 and fig 13. The side view is depicted in fig 12 and the front view is described in fig.13. The most important part that distinguishes the structures with SIW and without SIW is the via hole. The existence of via holes is clearly illustrated in fig.12. Inserted via holes connecting the groundplane with the radiator patch. It makes easy to flow the current from the exciting port to the radiator patch. Based on the color distribution of surface current, the numerical result shows that the highest surface current with SIW structure is 516 A/m at 28 GHz.

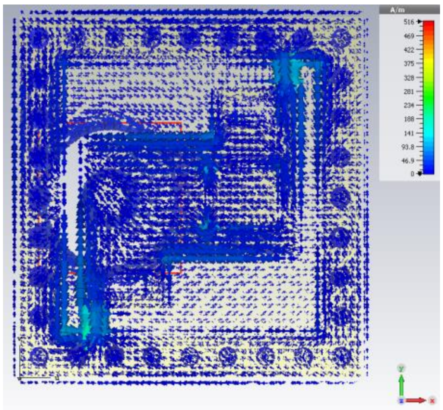

Fig. 13. Front view of surface current distribution with SIW structure

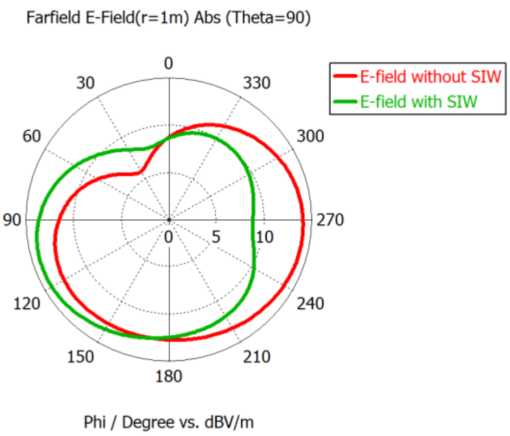

Fig. 14. A 2D of electrical field/E-field pattern at 28 GHz

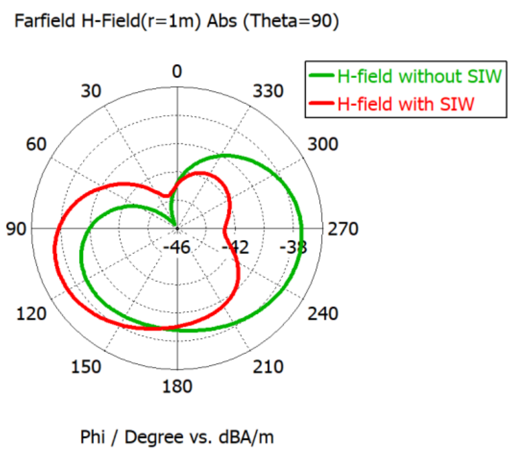

Fig. 15. A 2D of magnetic field/H-field pattern at 28 GHz

Figure 14 represents the E-field pattern (with ϴ = 90^{o}) for resonant frequency 28 GHz that radiates directionally and fig. 15 represents (with ϴ = 90^{o}) the H-field pattern that radiates also directionally. Basically, there is no significant difference in the E-field pattern either with SIW structure or without SIW structure. Based on fig. 14, there is a shift in the center of mainlobe of E-field pattern from 187^{o} (with SIW) to 214^{o} (without SIW). The H-field pattern is almost the same as the E-field pattern, shifting the center of mainlobe of H-field pattern from 120^{o} (with SIW) to 268^{o} (without SIW).

Figure 16 and fig. 17 represent the power pattern of antenna. The antenna without SIW structure produces a -5.71 dBW/m^2 of maximum power pattern density while maximum power pattern density with SIW structure is a - 5.06 dBW/m^2.

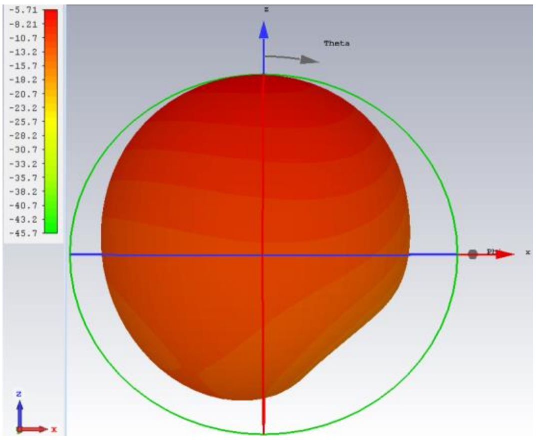

Fig. 16. A 3D of power pattern of the antenna without SIW structure at 28 GHz

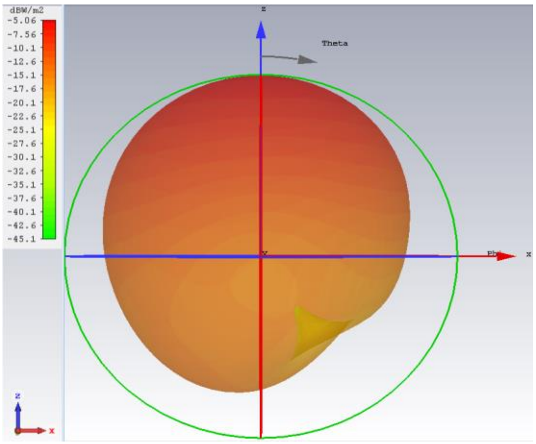

Fig. 17. A 3D of power pattern of the antenna with SIW structure at 28 GHz

CONCLUSION

Our proposed novel design of the U-slotted SIW antenna has a compact size of 5.2 mm x 5.2 mm. A square radiator patch optimized by using a rectangular truncated corner, after through several reiterated optimizations we get the optimized size of rectangular truncated corner is 2 mm x 0.8 mm with impedance bandwidth of 7.87 GHz (covering from 23.93 GHz to 31.8 GHz) at resonant frequency 28 GHz. Multiple metallic via-holes are drilled in a dielectric substrate establishing SIW cavity. Applying the U-shaped slot and SIW structure yield a wider impedance bandwidth, higher gain, and lower sidelobe level. Antenna with SIW structure produces a 6.24 dB of gain while without SIW just creates a 5.56 dB of gain.

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